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# BIDIRECTIONAL ACTUATORS

The present invention relates to the field of electromagnetic actuators.

Unidirectional actuators are known that use a stator structure excited by an electric coil, which produces a variable magnetic flux that ensures positioning of a movable magnet. For example, US Patent 4918987 describes such an actuator comprising a stator having two poles, each wound by a coil. The movable magnet is subjected to a linear force as a function of the flux generated by the coils.

There is also known German Patent DE 3037648, which describes a bidirectional actuator which may comprise either movable coils or movable magnets. The solution comprising movable coils is not satisfactory, because it leads to high industrialization costs. The described solution comprising movable magnets necessitates the use of 8 movable magnets. Such an architecture necessitates multiple control signals and information processing steps for fine control of the XY positioning process.

There is also known US Patent 5062055, which relates to electromagnetic actuators that produce a rotational and a translational movement simultaneously. Such a prior art actuator comprises a cylindrical magnet having magnetization fronts in the peripheral direction and in the axial direction, in which multipolar magnetization is established in the axial direction and yokes supporting coils have magnetic poles disposed facing the magnetization fronts. Such an actuator uses a magnet possessing several pairs of poles with magnetization directions that are perpendicular to one another.

The purpose of the present invention is to propose an actuator

capable of controlling the positioning of a device in two degrees of freedom, for example in a plane defined by two perpendicular axes XY, or in one translational degree of freedom and one rotational degree of freedom, or even in spherical rotation, with simple control signals.

To this end the invention relates in its most general sense to a bidirectional actuator comprising at least a stator structure excited by an electric coil and a single movable magnet having single polarity. This magnet is placed in a primary air gap. The stator structure is composed of two stator pieces. Each of the stator pieces is provided with at least one secondary air gap and is excited by at least one electric coil. The stator structure is provided with at least one air gap for displacement of the magnet which is movable relative to a first degree of freedom, and at least one secondary air gap for displacement of the magnet that is movable relative to a second degree of freedom.

In one particular embodiment, the movable magnet is integral with the yoke.

In a first alternative, the stator structure is composed of 4 poles of soft magnetic material, which define therebetween two pairs of secondary air gaps which cross at a central point and in that the primary air gap is planar.

Advantageously, the stator poles comprise two pairs of rectangular pieces, each pair of pieces being excited by at least one electric coil and each defining a secondary air gap.

Preferably the ratio L/E of the thickness L of the magnet and the thickness E of the air gap ranges between 1 and 2.

Advantageously, the dimensions of the secondary air gaps are $C_1 + E$ and $C_2 + E$, where $C_1$ and $C_2$ denote the travel range of the

movable magnet in the two directions of the secondary air gaps and in that the dimensions of the magnet are $C_1 + d_1 + E$ and $C_2 + d_2 + E$, $d_1$ and $d_2$ denoting the width of the said secondary air gaps.

According to a particular alternative, the stator structure is composed of two stator pieces disposed one on one side and one on the other of the magnet, each stator piece having a pair of stator poles, the pair of stator poles of one of the pieces being oriented perpendicular to the pair of stator poles of the other stator piece.

According to a second alternative embodiment, the magnet has tubular shape and is movable, in a first degree of freedom, by axial translation and, in a second degree of freedom, by axial rotation relative to a stator structure formed from 4 stator poles in the form of cylindrical segments, provided with a first secondary air gap in the longitudinal central plane, in which there is placed a first electric coil, and with a second secondary air gap in the transverse plane, in which there is placed a second coil. Each of these coils is preferably wound around a ferromagnetic core.

According to an alternative, the magnet has tubular shape and is movable, in a first degree of freedom, by axial translation and, in a second degree of freedom, by axial rotation relative to an external cylindrical stator structure formed from 4 stator poles having a concave surface defining the primary air gap with the cylindrical yoke placed inside the magnet, each of the four stator poles being wound by an electric coil.

According to another alternative, the magnet has tubular shape and is movable, in a first degree of freedom, by axial translation

and, in a second degree of freedom, by axial rotation relative to a cylindrical stator structure comprising a first external stator piece for displacement in a first degree of freedom and a second internal stator piece for displacement in a second degree of freedom, each of the stator pieces having at least one electric exciting coil.

According to a third embodiment, the magnet has spherical shape and is movable in spherical rotation relative to a stator structure in the form of a spherical cup formed from 4 stator poles in the form of cup sectors provided with two coils located in peripheral grooves whose central planes are perpendicular.

Advantageously, the magnet has spherical shape and is movable in spherical rotation relative to a stator structure of tubular shape formed from 4 stator poles in the form of tube quarters, wound by an electric coil.

According to a particular alternative of such an actuator, the primary air gap has spherical shape.

According to another particular alternative, the magnet has spherical shape and encloses a spherical cup, and is movable in spherical rotation around a stator structure of hemispherical shape formed from 4 stator poles in the form of sphere quarters.

According to a particular embodiment, the magnet has spherical shape and encloses a spherical yoke, and is movable in spherical rotation around a stator structure formed from two hemispherical stator pieces.

The invention will be better understood by reading the description hereinafter while referring to nonlimitative practical examples, illustrated by the attached drawings, wherein:

- Figs. 1 and 2 show schematic views which are respectively in cross section and of the stator part of a first alternative in the form of an XY linear actuator;

- Figs. 3a and 3b show the functioning of the actuator;

- Figs. 4 and 5 show views of an alternative embodiment of an XY actuator;

- Figs. 6 and 7 show schematic views which are respectively in cross section and of the stator part of a first alternative embodiment in the form of an XY linear actuator;

- Figs. 8 and 9 show an alternative of an x-$\theta$ cylindrical actuator, respectively without and with the magnet;

- Figs. 10 to 12 show views in perspective, respectively without and with the magnet, and in cross section, of a linear-rotary actuator;

- Figs. 13 to 16 show views in perspective, respectively without and with the magnet, and in cross-sectional view, and in exploded view, of a second version of a linear-rotary actuator;

- Figs. 17 to 19 show views in perspective, respectively without and with the magnet, and of the stator part of a third version of a linear-rotary actuator;

- Figs. 20 and 21 show an alternative embodiment of an actuator of the "external linear and rotary" type;

- Figs. 22 and 23 show a second version of an actuator of the "external linear and rotary" type;

- Figs. 24 and 25 show a third version of an actuator of the "external linear and rotary" type;

- Fig. 26 shows a first version of an alternative of the "Internal linear, external rotary" type;

- Figs. 27 and 27b show a modified version of an alternative of the "Internal linear, external rotary" type;

- Figs. 28 and 29 show, in three-quarters face view and in transverse view, a second version of an alternative of the "Internal linear, external rotary" type;

- Figs. 30 and 31 describe an actuator of the "external linear, internal rotary" type respectively in three-quarters face and in partial cutaway view;

- Fig. 32 shows a three-quarters face view of the stator assembly of an alternative of the "External linear, internal rotary" type;

- Figs. 33 and 34 show views of a spherical actuator and of the stator of such an actuator;

- Fig. 35 shows a view of a second version of a spherical actuator;

- Fig. 36 shows a view of a third version of a spherical actuator;

- Figs. 37 and 38 show three-quarters face and cross-sectional views of a fourth version of a spherical actuator;

- Figs. 39 and 40 show three-quarters face and cross-sectional views of a fifth version of a spherical actuator;

- Figs. 41 and 42 show three-quarters face and cross-sectional views of a sixth version of a spherical actuator;

- Figs. 43 and 44 show three-quarters face and cross-sectional

views of an actuator with position sensor.

The invention relates to a new type of actuator capable of displacing a movable part in two degrees of freedom.

The envisioned applications are:

- Information-processing applications: mouse, joystick
- Industrial applications: pick and place
- Automobile applications: gear-changing assistance.

Figs. 1 and 2 show views of a first practical example of an XY linear actuator.

The objective is to displace a movable part in a plane along 2 axes basically comprising a structure composed of a 4-pole stator, a movable magnet and a yoke that can be fixed or can move together with the magnet.

The first version presented with reference to Figs. 1 and 2 relates to a fixed-yoke actuator. In this architecture, therefore, only the magnet (14) is movable.

The actuator is then composed of the following functional parts:

- 1 flat magnet (14) composed of an isotropic or axially anisotropic magnetic alloy. In the latter case, the sense of the anisotropy must be perpendicular to the surface of the poles. It will be magnetized in this same direction.
- 1 yoke (5) of high-permeability magnetic material.
- 1 stator composed of a plane base (6) and of 4 poles (1 to 4) of rectangular cross section. It will also be made of high-permeability magnetic material.
- 4 coils (7 to 10), each wound around one of the stator poles. If necessary, a magnet support which will enclose the magnet

to transmit the force - or the displacement - applied to an external piece.

Any shape is conceivable for this latter support.

The functioning of this actuator can be explained as follows, with reference to Figs. 3a and 3b:

If the same current i1 is passed in coils (7) and (8) and a current i2 is passed in coils (9) and (10), a potential difference is created along the X axis: thus a force Fx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i3 is passed in coils (7) and (9) and a current i4 is passed in coils (8) and (10), there is created a force Fy which is proportional to the difference of magnetic potential and which is collinear with the Y axis.

This being established, it follows that, by combining the said currents, we will be able to create, by the principle of superposition, any force whose direction will lie in this plane XY.

In fact:

if, by supplying (7) and (8) by a current i1 and by supplying (9) and (10) by a current i2, there is created a force Fx

if, by supplying (7) and (9) by a current i3 and by supplying (8) and (10) by a current i4, there is created a force Fy

Then, by supplying (7) by i1 + i3, (8) by i1 + i4, (9) by i2 + i3 and (10) by i2 + i4, there is created a force Fx + Fy.

This actuator therefore makes it possible to create a force whose intensity and direction can be adjusted in the plane (XY).

Let L be the thickness of the magnet, E the air gap, $c_x$ and $c_y$ the travel ranges of the sensor in two dimensions and $d_x$ and $d_y$ the

pole-to-pole distances along the 2 axes.

It will be advisable to use a ratio L/E of between 1 and 2.

If $(c_x + E + d_x)$ and $(c_y + E + d_y)$ are taken for dimensions of the magnet and $(c_x + E)$ and $(c_y + E)$ are taken for minimum dimensions of the stator poles in the measurement plane, the linearity of the force as a function of the current will be effective on both axes.

Another architecture of this actuator can be imagined according to the alternative shown in Figs. 4 and 5.

The actuator is then composed of the following functional parts:

- 1 flat magnet (14) of rectangular shape, composed of an isotropic or axially anisotropic magnetic alloy. In the latter case, the sense of the anisotropy must be perpendicular to the surface of the poles. It will be magnetized in this same direction.
- 1 X stator (20) of high-permeability magnetic material, composed of a plane base (23) and of 2 poles (21, 22) of rectangular cross section.
- 1 Y stator (28) composed of a plane base (25) and of 2 poles (26, 27) with properties analogous to those of the X stator. These two poles (26, 27) are oriented perpendicular to the poles (21, 22) of the X stator.
- 2 X coils (31, 32), each wound around one of the poles (21, 22) of the X stator.
- 2 Y coils (36, 37), each wound around one of the poles (26, 27) of the Y stator.

The coils are flat coils wound around each of the stator poles.

If necessary, a magnet support which will enclose the magnet to transmit the force - or the displacement - applied to an external piece.

The X stator and the Y stator are disposed one on one side and

one on the other of the primary air gap in which the magnet (14) is placed. The poles (21, 22) of the X stator are oriented perpendicular to the poles (26, 27) of the Y stator, in order to urge the movable magnet in the two perpendicular directions and to ensure bidirectional displacement of the device to which it is coupled.

The functioning of this version can be explained as follows:

If a current i1 is passed in coil (31) and a current i2 is passed in coil (32), a potential difference is created along the X axis and thus a force Fx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i3 is passed in coil (36) and a current i4 is passed in coil (37), there is created a force Fy which is proportional to the difference of magnetic potential and which is collinear with the Y axis.

By combining the fine control of the currents in coils (X) and in coils (Y) independently of one another, it will be possible to create a force whose amplitude and direction are adjustable in the XY plane.

Figs. 6 and 7 show schematic views which are respectively in cross section and of the stator part of a first alternative embodiment in the form of an XY linear actuator;. This alternative of the actuator has the advantage that it necessitates only a single coil per axis.

The actuator is then composed of the following functional parts:

- 1 flat magnet (14) composed of an isotropic or axially anisotropic magnetic alloy. In the latter case, the sense of the anisotropy must be perpendicular to the surface of the poles. It will be magnetized in this same direction.
- 1 yoke (40) comprising a plate of high-permeability magnetic

material.

- 1 stator (41) composed of 4 poles (42 to 45) of rectangular cross section, connected by cores around which there are wound the coils (46, 47). It will also be made of high-permeability magnetic material. In the described example, it comprises a parallelepiped block provided with perpendicular central grooves for positioning the coils and defining the stator poles (42 to 45).
- 2 crossed coils (46, 47), wound around the stator (41) in two perpendicular directions.

If necessary, a magnet support which will enclose the magnet to transmit the force or the displacement applied to an external piece.

The functioning of this version can be explained as follows:

If a current i1 is passed in coil (46), a potential difference is created along the X axis and thus a force Fx proportional to the created difference of magnetic potential and therefore to current i1 is created along the X axis.

Similarly, if a current i3 is passed in coil (47), there is created a force Fy which is proportional to the difference of magnetic potential and therefore to current i2, and which is collinear with the Y axis.

It is then easily understood that, by combining the fine control of the currents in coils (46) and in coils (47) independently of one another, it will be possible to create a force whose amplitude and direction are adjustable in the XY plane.

This alternative can also be constructed in symmetric form, or in other words by replacing the yoke by an assembly of stator + coils. The amplitude of the created force will then be increased.

The stator can also be constructed in a plurality of

individual parts, for example by separating the poles. There can then be obtained a version without ferromagnetic coil core or provided with independent coil cores, which would make the winding process easier.

This alternative can also be constructed as a symmetric version.

Figs. 8 and 9 show an alternative of an x-$\theta$ cylindrical actuator, respectively without and with the magnet. Several versions are conceivable. The actuator has a cylindrical structure, which therefore comprises one zone inside the magnet and one zone outside this same magnet. This structure satisfies two functions to be assured: the function of a rotary actuator and of a linear actuator. The solutions described hereinafter will be defined by the situation ("internal" or "external") of each of these functions. In general, the actuator comprises a stator structure provided with four poles (51 to 54) in the form of half cylinders and a tubular magnet (55).

The description to follow will present first of all an actuator of the "Internal linear and rotary" type.

A first solution is described in Figs. 10 to 12: it comprises using a cylindrical internal stator composed of four identical poles. Two coils are wound around each of these poles.

The actuator is then composed of the following functional parts:

- 1 annular half magnet (60) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized. This can be independent or adhesively bonded to the yoke (61).
- 1 annular yoke (61) of high-permeability magnetic material.
- 1 stator composed of 4 poles (62 to 65) of cylindrical

external shape, connected by cores (70, 71) around which there are wound the coils (66 to 69). It will also be made of high-permeability magnetic material. Depending on manufacturing preferences, it may be made of a single piece or of an assembly of ferromagnetic pieces.

- 4 coils (66 to 69), wound around the stator.

The functioning of this actuator can be explained as follows:

If the same current i1 is passed in coils (66) and (67) and a current i2 is passed in coils (68) and (69), a potential difference is created along the X axis and thus a force Fx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i3 is passed in coils (66) and (68) and a current i4 is passed in coils (67) and (69), there is created in this case, on the magnet, a torque Mx which is collinear with the X axis and is proportional to the created difference of magnetic potential.

This being established, it follows that, by combining the said currents, we will be able to create, by the principle of superposition, any "force-torque" combination whose direction is collinear with the X axis.

In fact:

if, by supplying (66) and (67) by a current i1 and by supplying (68) and (69) by a current i2, there is created a force Fx

if, by supplying (66) and (68) by a current i3 and by supplying (67) and (69) by a current i4, there is created a torque Mx

Then, by supplying (66) by i1 + i3, (67) by i1 + i4, (68) by i2 + i3 and (69) by i2 + i4, there is created a force Fx and a torque Mx.

This actuator therefore makes it possible to create

simultaneously a force and a torque whose intensities are adjustable, both collinear with the X axis.

Figs. 13 to 16 show a second solution of a linear-rotary actuator.

This second solution comprises replacing 2 of the 4 coils of the preceding solution by one coil mounted on the primary axis of the mechanism. This, denoted (4L), will assure the "axial force" part and the 2 others will create the torque.

The actuator is then composed of the following functional parts:

- 1 annular half magnet (60) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized. This can be independent or adhesively bonded to the yoke.
- 1 annular yoke (61) of high-permeability magnetic material.
- 1 stator composed of 4 poles (62 to 65) of cylindrical external shape. The half moons facing one another radially are connected 2 by 2 by cores (70, 71) around which there are wound the coils (4R). The assemblies formed in this way will be connected by an axial core (72), around which there will be wound the coil (4L). All these poles will also be made of high-permeability magnetic material. Depending on manufacturing preferences, it may be made of a single piece or of an assembly of ferromagnetic pieces (see Fig. 16).
- 2 longitudinal coils (4R).
- 1 transverse coil (4L).

If necessary, a magnet support which will enclose the magnet to transmit the force - or the displacement - applied to an external piece.

The functioning of this actuator can be explained as follows:

If the current i1 is passed in the coil (4L), a difference in magnetic potential is created along the X axis: thus a force Fx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i2 is passed in coils (4R), there is created in this case, on the magnet, a torque Mx which is collinear with the X axis and is proportional to the created difference of magnetic potential.

This actuator therefore makes it possible to create simultaneously a force and a torque whose intensities are adjustable, both collinear with the X axis.

Figs. 17 to 19 show a third version of a linear-rotary actuator. The stator is formed by one cylindrical piece having 4 poles (62 to 65) in the form of half-cylinders. In this solution, the 2 coils noted in the foregoing (4R) are replaced by a single coil. Thus there are ultimately obtained 2 crossed coils, as illustrated in Figs. 17 to 19.

The functioning of this actuator can be explained as follows:

If a current i1 is passed in the coil (4L), a difference in magnetic potential is created along the X axis: thus a force Fx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i2 is passed in the coil (4R), there is created in this case, on the magnet, a torque Mx which is collinear with the X axis and is proportional to the created difference of magnetic potential.

This actuator therefore makes it possible to create simultaneously a force and a torque whose intensities are adjustable, both collinear with the X axis.

Another structure could also be obtained by dividing the coil (4L) into 3 or four coils mounted one on each side of the axial poles.

Figs. 20 and 21 show an alternative embodiment of an actuator of the "external linear and rotary" type.

All the versions described in this part are actually homologous versions of the versions described in the preceding part: the only difference is that the internal and external parts are interchanged. They will nevertheless be described for the sake of clarity.

In the version shown in Figs. 20 and 21 there are disposed four external coils, each wound around one pole.

The actuator is then composed of the following functional parts:

- 1 annular half magnet (80) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized. This can be independent or adhesively bonded to the yoke.
- 1 cylindrical yoke (81) of high-permeability magnetic material.
- 1 stator composed of 4 poles (82 to 85) of cylindrical internal shape, connected by a common base. It will also be made of high-permeability magnetic material. Depending on manufacturing preferences, it may be made of a single piece or of an assembly of ferromagnetic pieces.
- 4 coils (86 to 89), wound around the stator poles respectively (82 to 85).

If necessary, a magnet support which will enclose the magnet to transmit the force - or the displacement - applied to an external piece.

This version functions in a manner similar to the version shown by referring to Figs. 10 to 12:

In fact, by supplying (86) by i1 + i3, (87) by i1 + i4, (88) by i2 + i3 and (89) by i2 + i4, there is created a force Fx and a torque Mx.

This actuator therefore makes it possible to create simultaneously a force and a torque whose intensities are adjustable, both collinear with the X axis.

Figs. 22 and 23 show a second version of an actuator of the "linear-rotary" type.

The actuator is then composed of the following functional parts:

- 1 annular half magnet (90) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized. This can be independent or adhesively bonded to the yoke.
- 1 cylindrical yoke (95) of high-permeability magnetic material.
- 1 stator composed of 4 poles (91 to 94) and of a common structure (96). Around poles (91, 92) there are wound coils (4R) (97, 98). Coil (4L) will be situated between the poles as shown in Fig. 22. All these poles (91 to 94) will also be made of high-permeability magnetic material. Depending on manufacturing preferences, the whole may be made of a single piece or of an assembly of ferromagnetic pieces.
- 2 coils (4R).
- 1 coil (4L).

The functioning of this actuator can be explained as follows:

If the current i1 is passed in the coil (4L), a difference in magnetic potential is created along the X axis: thus a force Fx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i2 is passed in coils (4R), there is

created in this case, on the magnet, a torque Mx which is collinear with the X axis and is proportional to the created difference of magnetic potential.

This actuator therefore makes it possible to create simultaneously a force and a torque whose intensities are adjustable, both collinear with the X axis.

The coils (4L) and (4R) are shown here with rectangular shape to make it easy to read the drawing, but it is self-evident that they could also have, for example, cylindrical shape.

With a view to increasing the torque, it is also possible to dispose 4 coils (4R) in such a way that 2 are disposed on the 2 unused stator poles.

Figs. 24 and 25 show a third version of an actuator of the "linear-rotary" type, with 2 crossed coils. The actuator according to this third version is composed of the following functional parts:

- 1 annular half magnet (90) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized. This can be independent or adhesively bonded to the yoke.
- 1 cylindrical yoke (95) of high-permeability magnetic material.
- 1 stator composed of 4 poles (91 to 94) and of a common structure (96). Around 2 of those poles there will be wound coil (4R). Coil (4L) will be situated between the poles (91 to 94). All these poles will also be made of high-permeability magnetic material. Depending on manufacturing preferences, it may be made of a single piece or of an assembly of ferromagnetic pieces.
- 1 coil (4R).
- 1 coil (4L).

If necessary, a magnet support which will enclose the magnet to transmit the force - or the displacement - applied to an external piece.

The functioning of this actuator can be explained as follows:

If the current i1 is passed in the coil (4L), a difference in magnetic potential is created along the X axis: thus a force Fx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i2 is passed in the coil (4R), there is created in this case, on the magnet, a torque Mx which is collinear with the X axis and is proportional to the created difference of magnetic potential.

This actuator therefore makes it possible to create simultaneously a force and a torque whose intensities are adjustable, both collinear with the X axis.

Another structure could also be obtained by dividing the coil (4L) into 3 or four coils mounted one on each side of the axial poles, or by adding a second coil (4R), which is axially symmetric relative to the first.

Finally, for each of these versions, another structure could also be obtained by multiplying the stator structure by using a plurality of stators. In this way there is obtained a structure with more external poles, with a plurality of magnets, which offers a smaller angular travel range but a larger torque. In this way it is possible to imagine any structure of (2N) radial poles separated by angles of (360°/2N), with N magnets.

Fig. 26 shows a first version of an alternative of the "Internal linear, external rotary" type. The actuator is then composed of the following functional parts:

- 1 annular half magnet (100) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized. This must be independent of the two stators.
- 1 cylindrical stator of high-permeability magnetic material, composed of two poles (101, 102) of the same diameter. Coil (103) will be situated between these two poles, around a ferromagnetic core.
- 1 stator composed of 2 poles (104, 105) and of a common structure (108). Around them there will be wound coils (106, 107). These poles (104, 105) will also be made of high-permeability magnetic material. Depending on manufacturing preferences, this stator may be made of a single piece or of an assembly of ferromagnetic pieces.
- 1 coil (106).
- 1 coil (107).

If necessary, a magnet support which will enclose the magnet to transmit the force - or the displacement - applied to an external piece.

The functioning of this actuator can be explained as follows:

If a current i1 is passed in the coil (103), a difference in magnetic potential is created along the X axis: thus a force Fx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i2 is passed in coils (106, 107), there is created in this case, on the magnet, a torque Mx which is collinear with the X axis and is proportional to the created difference of magnetic potential.

This actuator therefore makes it possible to create simultaneously a force and a torque whose intensities are adjustable, both collinear with the X axis.

Another structure could also be obtained by multiplying the external stator structure according to Fig. 27. In this way there is obtained a structure with more external poles (110, 111, 112, 113), with a plurality of magnets (115, 116), which offers a smaller angular travel range but a larger torque. In this way it is possible to imagine any structure of (2N) radial poles. This multiplication principle can also be applied to each cylindrical structure described in this text.

Another structure could also be obtained by using only a single coil for creation of a torque. Figs. 28 and 29 show three-quarters face and cross-sectional views of such a version. This comprises a novel arrangement of the external part of the actuator such that only 2 coils are needed. The actuator is then composed of the following functional parts:

- 1 annular half magnet (120) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized. This must be independent of the two stators.
- 1 cylindrical stator of high-permeability magnetic material, composed of two poles (121, 122) of the same diameter. Coil (125) will be situated around this stator, between the 2 poles (121, 122).
- 1 stator composed of 2 poles (123, 124) and of a common structure. Coil (126) is wound around this stator, between the 2 poles (123, 124). These poles will also be made of high-permeability magnetic material. Depending on manufacturing preferences, this stator may be made of a single piece or of an assembly of ferromagnetic pieces.
- 1 coil (125).
- 1 coil (126).

If necessary, a magnet support which will enclose the magnet

to transmit the force - or the displacement - applied to an external piece.

The functioning of this actuator can be explained as follows:

If a current i1 is passed in the coil (125), a difference in magnetic potential is created along the X axis: thus a force Fx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i2 is passed in the coil (126), there is created in this case, on the magnet, a torque Mx which is collinear with the X axis and is proportional to the created difference of magnetic potential.

This actuator therefore makes it possible to create simultaneously a force and a torque whose intensities are adjustable, both collinear with the X axis.

Figs. 30 and 31 describe an actuator of the "External linear, internal rotary" type.

The actuator is composed of the following functional parts:

- 1 annular half magnet (140) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized. This must be independent of the two stators.
- 1 cylindrical stator of high-permeability magnetic material, composed of two poles (141, 142) of the same diameter. Coil (143) will be situated between the 2 poles.
- 1 stator (2R) composed of 2 poles (144, 145) and of a common core. Coil (146) will be situated such that it is wound around this core, between the 2 poles (144, 145). These poles will also be made of high-permeability magnetic material.
- 1 coil (143).

- 1 coil (146).

If necessary, a magnet support which will enclose the magnet to transmit the force - or the displacement - applied to an external piece.

The functioning of this actuator can be explained as follows:

If a current i1 is passed in the coil (143), a difference in magnetic potential is created along the X axis: thus a force Fx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i2 is passed in the coil (146), there is created in this case, on the magnet, a torque Mx which is collinear with the X axis and is proportional to the created difference of magnetic potential.

This actuator therefore makes it possible to create simultaneously a force and a torque whose intensities are adjustable, both collinear with the X axis.

It is to be noted that, by constructing the stator in the form of four quarter cylinders (150 to 153), around which there are wound 2 coils (154, 155) (see Fig. 32), there is obtained a version with 4 poles in rotational direction, having a reduced travel range of less than 90° but furnishing a larger torque. There will then be used 2 magnets with angular width of 90°.

Figs. 33 and 34 show views of an $\alpha$-$\beta$ spherical actuator and of its stator.

Several versions are conceivable. The solutions described hereinafter will be defined by the ("internal" or "external") situation of the two functions (rotation around 2 axes) assured by the actuator.

The actuator is composed of the following functional parts:

- 1 spherical half magnet (200) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized. This can be independent or adhesively bonded to the yoke, as shown in the figure (33).
- 1 hollow spherical yoke (201) of high-permeability magnetic material.
- 1 stator composed of 4 poles (202 to 205) of spherical external shape, connected by cores around which there will be wound the four coils (206 to 209). It will also be made of high-permeability magnetic material. Depending on manufacturing preferences, it may be made of a single piece or of an assembly of ferromagnetic pieces.
- 4 coils (206 to 209), wound around the stator.

If necessary, a magnet support which will be fixed to the magnet to transmit the force - or the displacement - applied to an external piece.

The functioning of this actuator can be explained as follows:

If the same current i1 is passed in the coils (206) and (208), a difference in potential with respect to rotation around the X axis is created and thus a torque Mx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i2 is passed in the coils (207) and (209), there is created in this case, on the magnet, a torque My which is collinear with the Y axis and is proportional to the created difference of magnetic potential.

By combining the said currents, we will be able to create, by the principle of superposition, any torque whose axis will lie in this plane XY.

In fact:

By supplying (206) and (208) by a current i1, there is created

a torque Mx

By supplying (207) and (209) by a current i2, there is created a torque My

Then, by supplying (206) and (208) by i1, (207) and (209) by i2, there are created a torque Mx and a torque My.

This actuator therefore makes it possible to create independent torques along two orthogonal axes.

Fig. 35 shows a second version of a spherical actuator. The actuator is composed of the following functional parts:

- 1 spherical half magnet (210) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized. This can be independent or adhesively bonded to the yoke, as shown in the figure (35).
- 1 hollow spherical yoke (211) of high-permeability magnetic material.
- 1 stator composed of 4 poles (212 to 215) of spherical external shape, connected by cores around which there will be wound the coils (216, 217). It will also be made of high-permeability magnetic material. Depending on manufacturing preferences, it may be made of a single piece or of an assembly of ferromagnetic pieces.
- 2 crossed coils (216) and (217), wound around the stator.

If necessary, a magnet support which will be fixed to the magnet to transmit the force - or the displacement - applied to an external piece.

The functioning of this actuator can be explained as follows:

If a current i1 is passed in the coil (216), a difference in potential with respect to rotation around the X axis is created and thus a torque Mx proportional to the created difference of magnetic

potential is created along the X axis.

Similarly, if a current i2 is passed in the coil (217), there is created in this case, on the magnet, a torque My which is collinear with the Y axis and is proportional to the created difference of magnetic potential.

By combining the said currents, we will be able to create, by the principle of superposition, any torque whose axis will lie in this plane XY.

Fig. 36 corresponds to another arrangement of this same system, which can be more easily constructed industrially but which has a shorter travel range.

The stator parts are constructed in the form of spherical sector quarters (220 to 223). They are wound by two coils (224, 225).

Figs. 37 and 38 show views of a spherical actuator of the "All external" type.

The principle of this solution comprises interchanging the architecture of the preceding actuator, by placing the yoke and magnet inside and the stator poles outside.

The first version of this actuator is composed of the following functional parts:

- 1 magnet in the form of a spherical cup (230) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized.
- 1 spherical yoke (231) of high-permeability magnetic material.
- 1 stator composed of 4 poles (232 to 235) having external shape in the form of cylinder quarters and spherical internal shape, connected by cores around which there will be wound the coils (236 to 239). It will also be made of high-permeability

magnetic material. Depending on manufacturing preferences, it may be made of a single piece or of an assembly of ferromagnetic pieces.

- 4 coils (236 to 239), wound around the stator, 2 per axis of rotation.

If necessary, a magnet support which will be fixed to the magnet to transmit the force - or the displacement - applied to an external piece.

The functioning of this actuator is in every respect the same as that of the first spherical actuator described in this text.

Figs. 39 and 40 show a second version of a spherical actuator of the "all external" type.

The actuator is composed of the following functional parts:

- 1 magnet in the form of a spherical cup (250) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized.
- 1 spherical yoke (251) of high-permeability magnetic material.
- 1 stator composed of 4 poles (252 to 255) of spherical internal shape, connected by cores around which there will be wound the coils (256, 257). It will also be made of high-permeability magnetic material. Depending on manufacturing preferences, it may be made of a single piece or of an assembly of ferromagnetic pieces.
- 2 coils (256, 257), wound around the stator, 1 per axis of rotation.

The functioning of this actuator is in every respect the same as that of the spherical actuator illustrated in Figs. 35 and 36.

Figs. 41 and 42 show three-quarters face and partial cutaway views of a hybrid actuator (internal and external).

The actuator is composed of the following functional parts:

- 1 magnet in the form of a spherical cup (260) composed of an isotropic or radially anisotropic magnetic alloy, which is radially magnetized. This must be independent of the two stators.
- 1 internal stator, of spherical external shapes, of high-permeability magnetic material. It has 2 poles (261, 262) connected by a core, around which there is wound the coil (265).
- 1 external stator composed of 2 poles (263, 264) of spherical internal shape, connected by a core around which there will be wound the coil (266). It will also be made of high-permeability magnetic material.
- 1 coil (266), wound around the external stator.
- 1 coil (265), wound around the internal stator.

If necessary, a magnet support which will be fixed to the magnet to transmit the force - or the displacement - applied to an external piece.

The functioning of this actuator can be explained as follows:

If a current i1 is passed in the coil (266), a difference in potential with respect to rotation around the X axis is created and thus a torque Mx proportional to the created difference of magnetic potential is created along the X axis.

Similarly, if a current i2 is passed in the coil (265), there is created in this case, on the magnet, a torque My which is collinear with the Y axis and is proportional to the created difference of magnetic potential.

By combining the said currents, we will be able to create, by the principle of superposition, any torque whose axis will lie in this plane XY.

Each of the foregoing electromagnetic systems can be coupled with contactless dimensional position sensors.

There will then be obtained a "sensor-actuator" assembly capable of assuring two functions in the same volume and thus of working in closed-loop manner.

For this purpose the iron parts between the stator poles (in other words, those around which the coils will be wound, generally referred to as "core" throughout this patent) must be separated by means of a slot.

An element that is sensitive to magnetic fields (such as a Hall-effect sensor) will then be positioned in the said slot.

Figs. 43 and 44 illustrate the application of this principle to a plane XY actuator.

The position sensor makes it possible to measure the flux variations created by a magnet that is movable in an air gap.

The stator comprises four rectangular parts (300 to 303) wound by four coils (310 to 313). A thin transversely magnetized magnet (305) is placed in the primary air gap (307) formed between the stator and the yoke (306). Four Hall sensors (320 to 323) are placed in the secondary air gaps between the stator parts (300 to 303).

In the described architecture, the sensors will measure a flux variation due to the displacement of the magnet and to the current circulating in the coils. We must therefore "separate" this flux due to the current. This can be accomplished in two ways:

By measuring the current in the coils and calculating the flux induced by the current, to subtract it from the measured value. In fact, the total flux is the sum of the flux due to the current and of the flux due to the magnet ($\Phi t = \Phi ni + \Phi a = A.ni + \Phi a$). Knowing

the impedance A of the magnetic circuit and the current in the coils, it is easily possible to calculate Φa. The intensity can be measured by any conceivable means (for example, by recording the voltage drop at the leads of a sampling resistor through which the said current is passing).

By alternating the "sensor" and "actuator" functions. During a given time interval, the coils will be supplied in order to produce the desired force (or torque) and, during the following interval, the supply of the coils will be suspended in order that only the flux due to the magnet is now being measured. Thus there will be obtained an intermittent force that can be used for functions of the joystick type.